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Nonintrusive Flow Rate Determination Through Space Shuttle Water Coolant Loop Floodlight Coldplate

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BACKGROUND

Space Shuttle crew module cooling (for electronics and crew comfort) entails flowing cold water through stainless steel coldplates with a face sheet thickness of 0.012 inch and a pipe diameter of 0.25 inch. The individual electronics (black boxes) are mechanically attached to the coldplates and are cooled by the cold water flowing through the coldplate. Heat is removed from the black boxes by thermal conduction. There are two separate and identical redundant water coolant loops (WCL's) that circulate cool water through all the heat exchangers and coldplates in the crew module. The plumbing for the WCL's is located inside the crew module, except for one coldplate and approximately 25 feet of exposed tubing behind the crew compartment and in the payload area (see figure 1). The payload section of the tubing is used to cool a floodlight assembly and experiences the harsh temperature extremes of space.

During space flight operations, only one of the two redundant WCL's (WCL2) is used. The water in the other loop (WCL1) is stagnant except for intervals of operation designed to prevent ice formation in the section of the tubing exposed to space. Original intervals of operation were 50 hours. This was reduced to 4 hours after a blister was found on the Space Shuttle Atlantis' Freon-to-water interchanger that was due to ice forming in the heat exchanger. Currently, there is no in situ flow measurement device in this portion of the WCL to measure actual flow through the floodlight coldplate. Flow through the floodlight coldplate was originally calculated to be 35 ±3 pounds per hour by Rockwell using a hydraulic model. However, this represented the first effort to validate the computed flow rates.

PROBLEM STATEMENT

During installation of the floodlight assembly on the Space Shuttle Discovery, a bulge/blister was discovered on the inlet side of the coldplate, similar to one found on the Freon-to-water interchanger of the Space Shuttle Atlantis after completion of the STS-66 mission in February 1995. As part of the troubleshooting, a determination of the actual flow rate through the affected coldplate was sought. Early theories suggested there could have been a potential block inside the affected coldplate, contributing to the reduced flow and subsequent ice formation. The objective

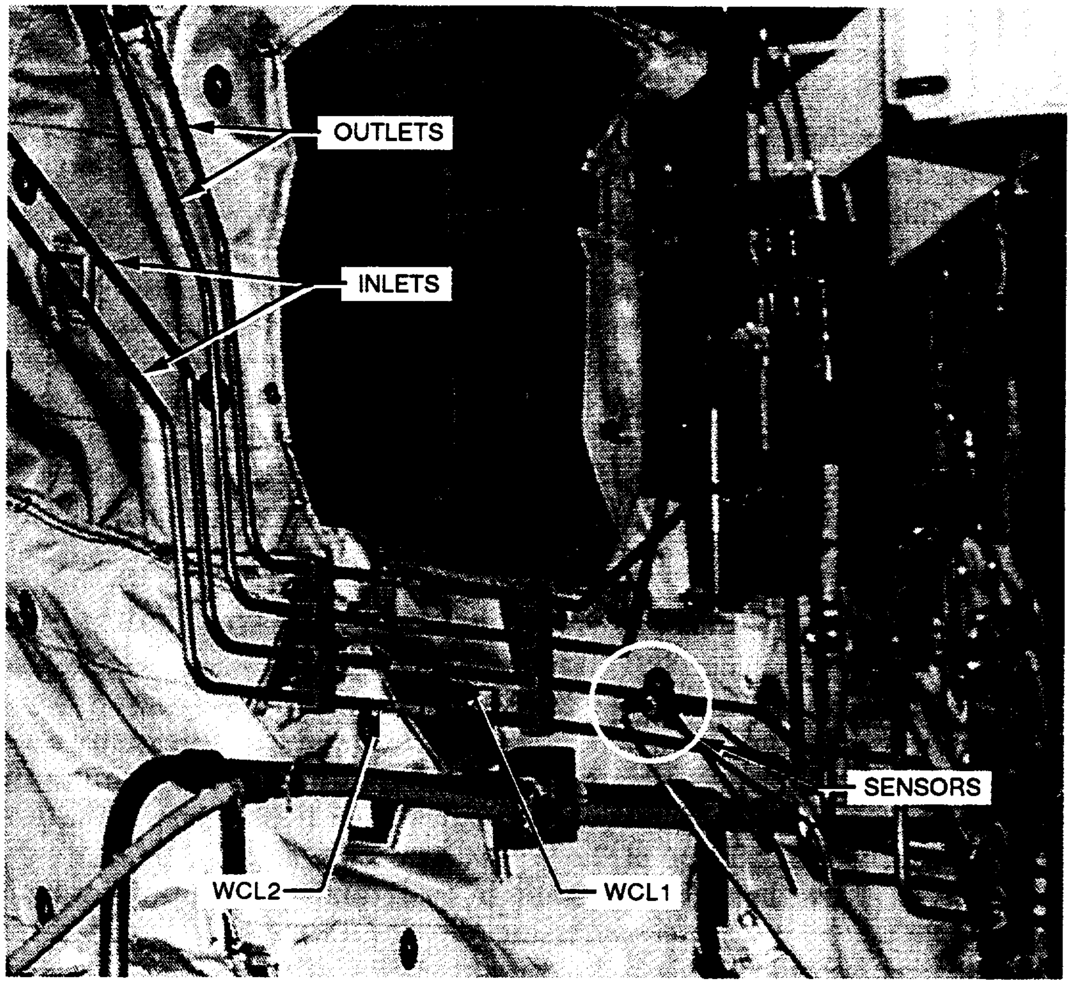


Figure 1. Plumbing for the WCL1 Showing the Installation of the Ultrasonic Flow Sensor

of in situ ultrasonic flow measurements was to prove or disprove this hypothesis while validating the hydraulic model by measuring the actual flow rates. Table 1 is a chronological summary of the present validation effort.

NONINTRUSIVE FLOW MEASUREMENT SYSTEM

The problem as stated above posed a unique opportunity for extending the application of ultrasonic flowmeter technology used recently by NASA DM-ASD and I-NET engineers for precise measurement and validation of hypergol (monomethylhydrazine and nitrogen tetroxide) fill rates to the orbiter (NASA-TM-111884, Space Shuttle Hypergol Load Determination Using Noninstrusive Ultrasonic Flowmeters). The capability to predict hypergol fill loads to within 1 percent of the actual load was demonstrated using ultrasonic flowmeter technology. In this application, relatively larger diameter piping (1 inch) coupled with significantly higher flow rates (over 1,000 pounds per hour) were within the bounds of ultrasonic flow technology. This technology provided a nonintrusive capability and eliminated hazardous SCAPE operations.

In the present application, the critical nature of flight hardware meant the use of a nonintrusive flow measurement system (NFMS) was the only choice. Moreover, features of portability and significant ease of measurement provided an impetus for the ultrasonic flowmeter technique to be applied. However, 0.25-inch-diameter pipe sizes coupled with extremely low flow rates (5 to 30 pounds per hour) meant the measurement range of ultrasonic flowmeters needed to be extended. Manufacturer's data sheets recommended that 1/2 inch was the minimum pipe diameter for flow measurement. In short, the state of the art was being overextended. Since there were no other alternatives, it was decided to coordinate closely with the manufacturer and proceed with caution.

Ultrasonic Flowmeter (UFM)

A highly versatile, self-contained, portable Panametrics TransPort Model PT868 UFM was adopted for the measurement. The proposed nonintrusive flowmeter system is composed of a pair of 4-megahertz transducers that are clamped onto the outside of the pipe and use the transit-time flow measurement technique (see figure 2). The sensor spacing is a function of pipe type, pipe size (outside and inside diameters), and the characteristics of the fluid (temperature, fluid type, etc.) for which the flow rate will be measured. The two transducers serve as an ultrasonic signal generator and a receiver and are in acoustic communication with each other.

Table 1. Chronology of In Situ Measurements and Calibration Activity

1. Prior to the removal and replacement of the coldplate on Discovery:	
9/11/96	Performed in situ measurements on Discovery using the three-traverse method; instantaneous flow velocities were documented; no time flow checks were made; meter was not zeroed
9/30/96	Flow calibration check was performed at the NASA Prototype Shop
10/18/96	Panametric factory performed flow calibrations
2. After the removal and replacement of the coldplate on Discovery:	
11/5/96	Performed in situ measurements on Discovery using the two-traverse method; instantaneous flow velocities and timed flow checks were documented; meter was not zeroed
11/14/96	Flow calibration check was performed at the NASA Prototype Shop
11/15/96	Performed in situ measurements on Atlantis using the two-traverse method; instantaneous flow velocities and timed flow checks were documented; meter was not zeroed
11/26/96	Performed in situ measurements on Discovery using the two-traverse method; instantaneous flow velocities and timed flow checks were documented; meter was zeroed using a +0.4-nanosecond correction

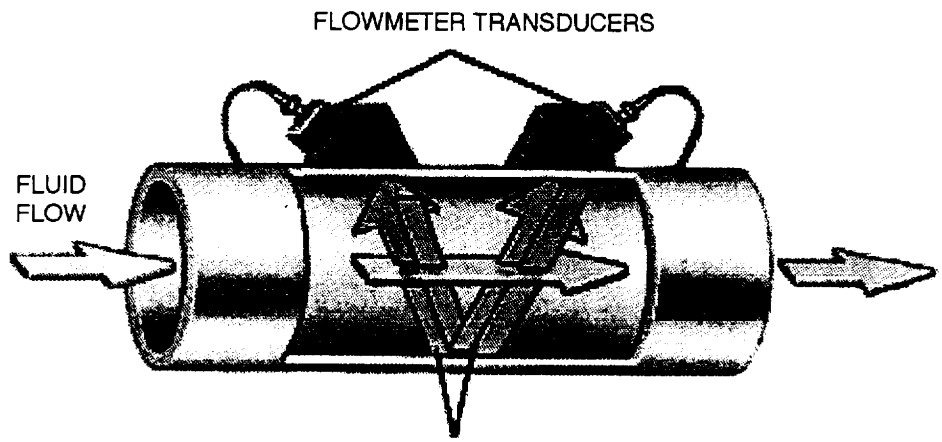


Figure 2. Transmit-Time Flow Measurement Technique

In operation, each transducer functions as a transmitter generating a certain number of acoustic pulses and then as a receiver for an identical number of pulses.

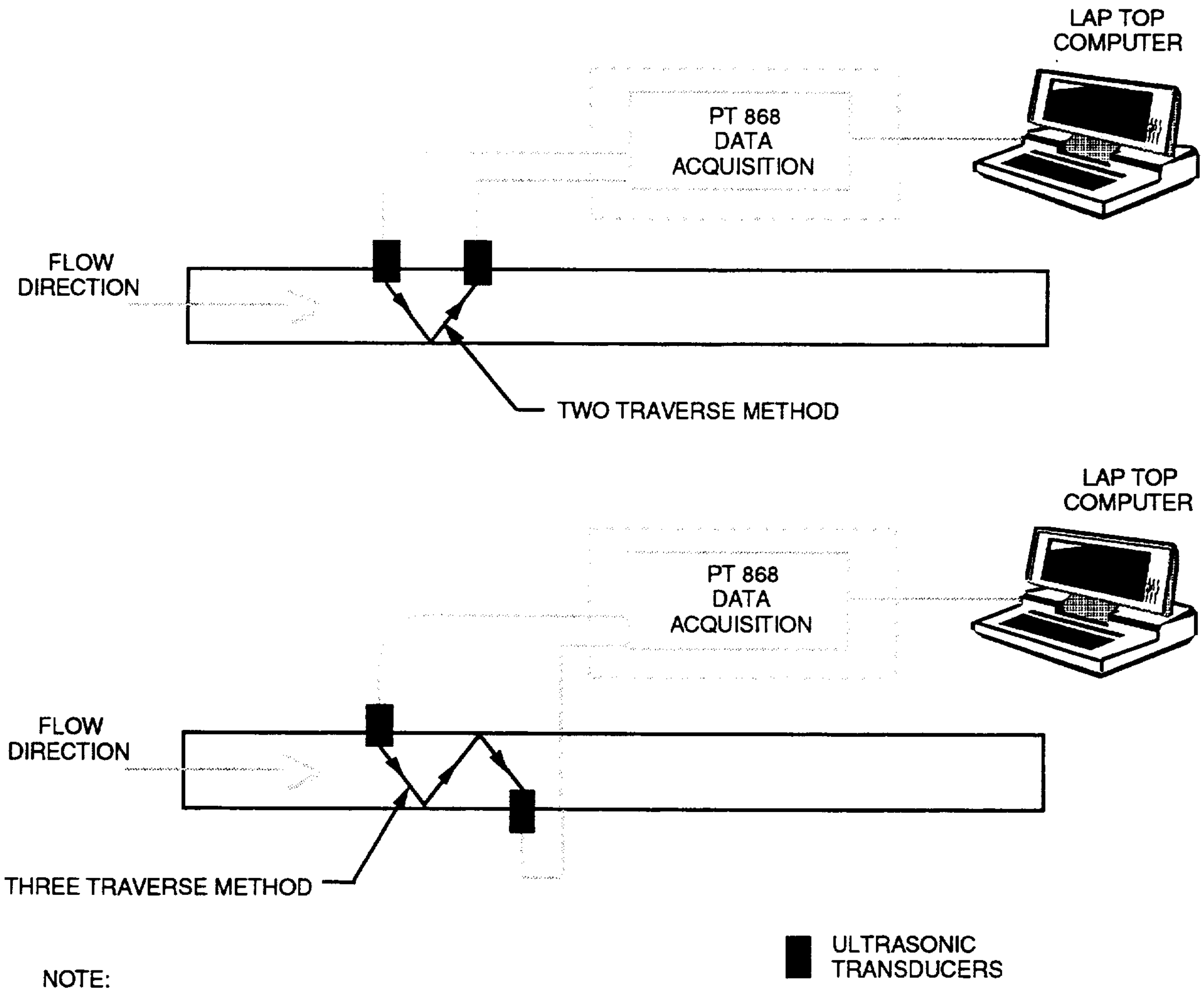
The time interval between the transmission and reception of the ultrasonic pulses is measured in both directions. When the liquid in the pipe is not flowing, the transit time downstream equals the transit time upstream. When the liquid is flowing, the transit time downstream is less than the transit time upstream. The difference between the downstream and upstream transit times is proportional to the flow rate or velocity of the flowing liquid, and its sign indicates the direction of the flow. From the knowledge of flow velocity, other flow-related parameters such as volumetric flow and total flow are computed.

The TransPort flowmeter uses built-in digital signal processing (DSP) techniques to display a variety of flow-related parameters (see figure 3). Measurements can be monitored and logged in real time. Use of nonintrusive clamp-on transducers means no leaks, corrosion, or contamination problems will arise as a result of their use. In addition to accessibility to the WCL's, portability of instrumentation, coupled with foreign object damage with leftover residues, was a major concern since the measurements were to be made on the actual Space Shuttle flight hardware.

Factory Calibration Check

In addition to flow measurement accuracy checks performed at the NASA/KSC Prototype Shop, a bench calibration was performed by Panametrics factory personnel. The purpose of this calibration was to evaluate flow measurement errors especially at very low flow rates (between 0 to 50 pounds per hour). In addition, small diameter pipe meant that the uncertainties associated with the methods of two traverses or three traverses of the ultrasonic beam needed to be established.

To closely simulate the Space Shuttle conditions, the exact sensors and cabling to be used and a portion of the 1/4-inch tubing used on the Space Shuttle were sent to the factory for bench calibration. Flow verification was performed on an open-loop system at four different flow rates varying from 5 to 180 pounds per hour. A two-traverse method with wider sensor spacing between the transducers was found to be the most reliable method. Rather than using the sensor distance computed by the ultrasonic flowmeter software, a wider spacing was programmed to yield a strong signal. The wider spacing of 0.4 inch was controlled by placing a 1/8-inch shim of ultrasonic absorbing material made of Sorbathane between the two sensors. The Sorbathane also avoided acoustic short circuiting and signal skipping problems encountered while using the three-traverse method.



NOTE:

SIGNAL PROCESSING CALCULATES THE DELTA TIME BASED ON THE DIFFERENCE IN TRANSIENT TIME WITH FLOW AND AGAINST FLOW. THE TRANSDUCERS BOTH SEND AND RECEIVE ULTRASONIC PULSES.

Figure 3. Typical In Situ Installation

Results from the factory provided a good understanding of the errors attributable to the use of the number of traverses, the effects of temperature, the transducer spacing, and the zeroing of the meter to account for delta T offset prior to the tests. The delta T offset accounts for any variation in cable lengths between the upstream and downstream sensors that may cause the meter to indicate the transit time to be non-zero under no-flow conditions. In general, with the three-traverse method, errors in the range of 9 to 21 percent were observed. When the two-traverse method was used, the error between the meter totalizer and the flow computed from the fluid weight was reduced to 12 to 15 percent. The ultrasonic meter typically indicated higher flow rates than those actually experienced. The factory calibration is summarized in table 2.

It was concluded that the two-traverse method with 0.4-inch sensor spacing would be beneficial for Space Shuttle application. The sensors, together with cabling and Sorbathane material, were returned to KSC for Space Shuttle measurement.

Sensor Installation

Figure 4 shows the open cargo bay door of the Space Shuttle Discovery (OV-103) inside the Orbiter Processing Facility (OPF). Access to the coldplate was facilitated by a platform attached to an overhead crane. The platform was carefully positioned in close proximity to the coldplate located on the back of the crew cabin facing the Orbiter cargo bay (see figure 5). Figure 1 shows the installation of the ultrasonic flow sensors on WCL1. The top two pipes are outlets, and the bottom two are inlets. WCL2 is directly below WCL1. The direction of water flow in the inlet pipes of WCL1 and WCL2 is left to right.

Ultrasonic flow sensors were held on the stainless steel pipe by plastic tie wraps. A straight section of the stainless steel pipe approximately 6 to 10 times the pipe diameter was used for application. The purpose of this was to ensure the flow pattern as measured by upstream and downstream sensors was not disturbed by bends in the pipe. Even the cabling needed to be tie wrapped, since it pulled the sensors under gravity loads causing disorientation of the sensors and contributing to erroneous readings.

The ultrasonic flowmeter and a laptop computer were located in the bucket. Although flow readings could be read from the ultrasonic flowmeter itself with a laptop computer, other flow-related parameters such as signal strength, sound speed, flow velocity, total flow rate, etc., could be monitored real time. Extreme

Table 2. Factory Calibration Results

Three-Traverse Method (Meter Zeroed)*							
	Ultrasonic Flowmeter			Fluid Weight			
Timed Flow (min)	Flow (total gal)	Flow Rate (gal/min)	Flow Rate (lb/hr)	Flow (total gal)	Flow Rate (gal/min)	Flow Rate (lb/hr)	Percent Error Between Ultrasonic and Fluid Weight
4.227	0.058	0.014	6.852	0.049	0.012	5.788	18.367
2.770	0.082	0.030	14.782	0.075	0.027	13.520	9.333
1.305	0.102	0.078	39.029	0.092	0.070	35.203	10.870
0.315	0.139	0.438	218.955	0.115	0.363	181.149	20.870

Two-Traverse Method (Meter Zeroed)**							
	Ultrasonic Flowmeter			Fluid Weight			
Timed Flow (min)	Flow (total gal)	Flow Rate (gal/min)	Flow Rate (lb/hr)	Flow (total gal)	Flow Rate (gal/min)	Flow Rate (lb/hr)	Percent Error Between Ultrasonic and Fluid Weight
3.923	0.053	0.014	6.746	0.047	0.012	5.982	12.766
3.083	0.070	0.023	11.338	0.062	0.020	10.042	12.903
1.615	0.118	0.073	36.484	0.106	0.066	32.774	11.321
0.880	0.129	0.147	73.199	0.112	0.127	63.553	15.179

*Sensor spacing = 0.331 inch, ΔT offset = 0.4 nanosecond, and fluid temperature = 71.6 °F.

**Sensor spacing = 0.4 inch, ΔT offset = 0.4 nanosecond, and fluid temperature = 71.6 °F.

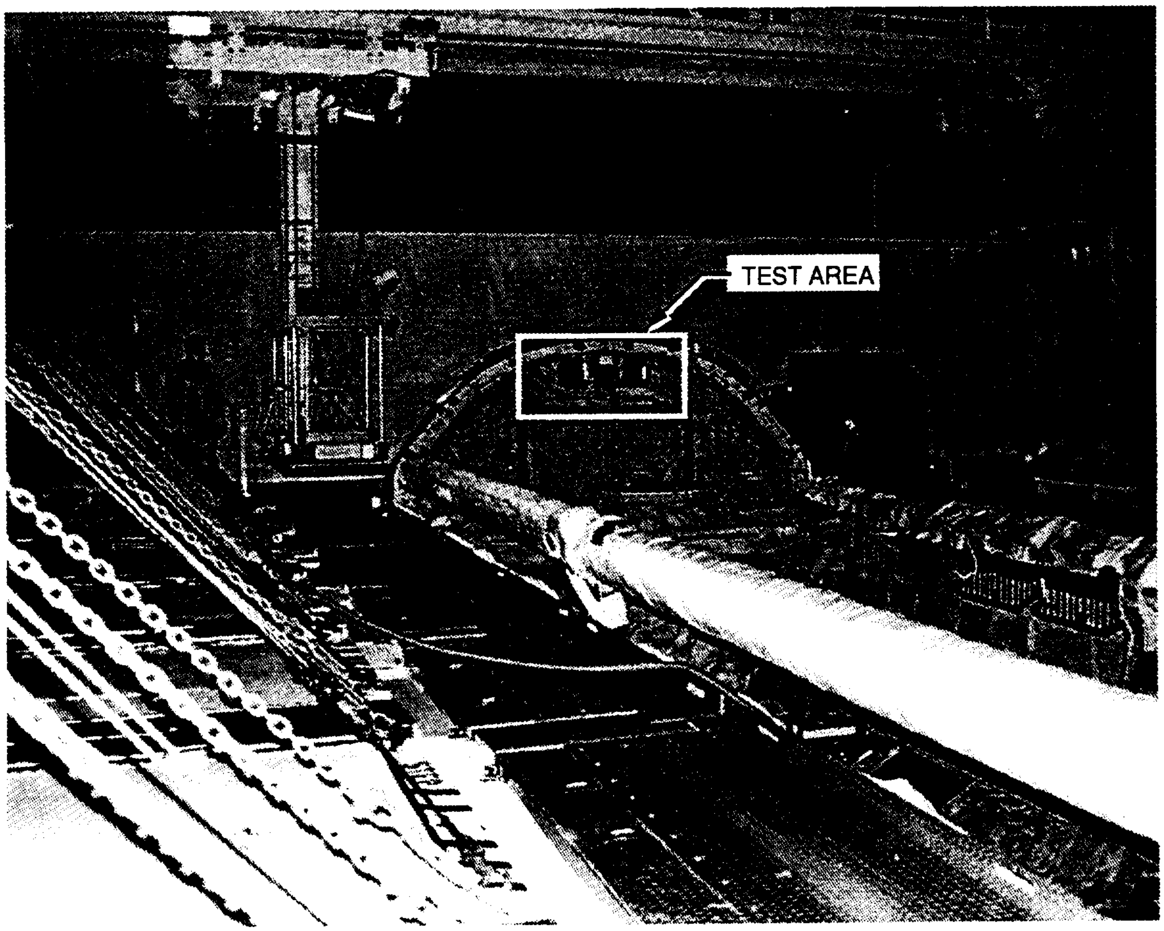


Figure 4. Open Cargo Bay of Space Shuttle Discovery

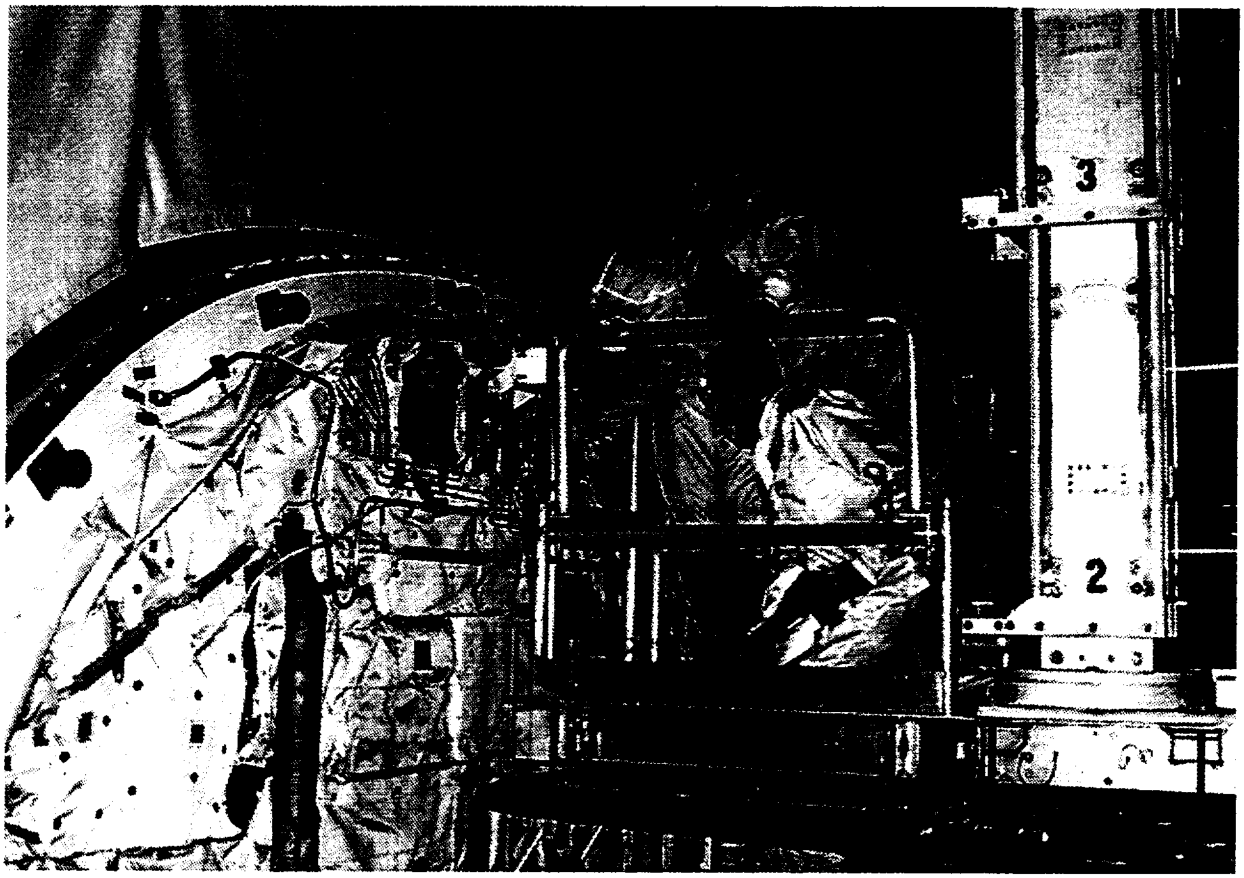


Figure 5. Test Area Located on the Back of the Crew Cabin Facing the Orbiter Cargo Bay

care was taken so no residue or foreign object was left once the measurements were completed. The two-traverse method was used for all measurements. This method reads two traverses of the ultrasonic beam across the pipe. In this configuration, the two ultrasonic sensors were located on the same side of the pipe since this method provided more reliable measurements in the factory. The tests were conducted with and without the delta T offset.

In Situ Flow Rate Measurements

To date, ultrasonic flowmeters have been used to determine flow rate through the Space Shuttle water coolant loop floodlight coldplate on four occasions (see table 1). In each case, flow rates through WCL1 and WCL2 pipes were measured. The first measurement was made on Discovery on September 11, 1996, prior to the removal and replacement of the affected coldplate. This flow rate determination used the three-traverse method and checked only flow velocities rather than timed flows. Chronologically, this quick check was performed prior to factory calibrations that were completed between October 17 and 18, 1996. Instantaneous velocities are prone to fluctuations; hence, all subsequent checks were made using 5 to 8 minutes of timed flow to smooth out inconsistent flow patterns.

Subsequent measurements on Discovery were performed on November 5 and 26, 1996, and reflect conditions after the replacement of the coldplate. These checks used the two-traverse method and timed flow approach to determine flow rates. Similar techniques were used on Atlantis (OV-104) on November 5, 1996. For brevity, only the post-replacement data from Discovery is compared with that from Atlantis (see tables 3 and 4). This comparison was necessary to ensure there was no unique, low-flow condition for Discovery when compared with other orbiters. Atlantis was the only orbiter available at the time of this study for verification.

RESULTS AND DISCUSSION

During the short span of time between when initial and final in situ measurements were made, significant strides were made in understanding the flow rates and patterns through the Space Shuttle water coolant loop floodlight coldplate. To establish confidence in the measurements, tests were performed on both active (flowing) inlet tubes in WCL1 and WCL2. Moreover, the flow rates were cycled from no flow to full or nominal flow for each inlet tube to evaluate the effectiveness of a nonintrusive measurement technique to quickly measure the changes. The NFMS was able to detect the flow rate variations quickly and accurately. Also, a comparative evaluation of instantaneous flow velocities to timed flow rates was performed. Timed flowrates were accomplished by reading the cumulative flow as indicated by the ultrasonic flowmeter at 1-minute intervals for a period of 5 to 8 minutes and

Table 3. Comparison of Discovery and Atlantis Flow Checks Prior to the Meter Being Zeroed*

Discovery		
Timed Flow (minute)	Flow Through WCL1 Inlet (lb/hr)	Flow Through WCL2 Inlet (lb/hr)
1	12.5	19.5
1	9.5	19.0
1	8.5	18.5
1	12.0	19.5
Average	10.62	19.13

Atlantis		
Timed Flow (minute)	Flow Through WCL1 Inlet (lb/hr)	Flow Through WCL2 Inlet (lb/hr)
1	16.5	22
1	19	20.5
1	18	21
1	16.5	21
1	17	21.5
1	16.5	18.5
1	18	20
1	15.5	22
Average	17.12	20.8

*Sensor spacing = 0.4 inch and water temperature = 75.3 °F.

Table 4. Ultrasonic Flow Checks on Discovery After Meter Was Zeroed

Timed Flow (minutes)	Flow Through WCL1 Inlet (lb/hr)	Flow Through WCL2 Inlet (lb/hr)
1	22.5	24
1	21	24.5
1	21	23.5
1	23	24
1	22	24
1	21	--
1	20	--
Average	21.5	24
Atlantis flow rate adjusted upwards to reflect meter zero correction (see table 3):		
Average	17.12 + 8 = ≈25	20.8 + 8 = ≈29

by obtaining the difference between subsequent readings. This provided an average flow rate for the timed period. Tables 3 and 4 summarize the data obtained from in situ measurements on the Space Shuttles Discovery and Atlantis before and after the meter was zeroed.

Table 3 compares the measurements on Discovery (November 5, 1996) to those from Atlantis (November 15, 1996). On an average, both vehicles experienced similar flow rates through the coldplate in WCL2. The individual flow rates, however, are all lower than the design flow requirements (35 pounds per hour). Also, the WCL1 inlet on Discovery was somewhat lower than the rest. Additional review of the data indicated that the meter exhibited an electronic offset of 0.4 nanosecond. In most applications where the flow rates are higher, this offset is trivial. However, when extremely low flow rates are in question, this offset must be accounted for by zeroing the meter prior to all measurements. It was decided to perform another check on Discovery as had been done at the factory.

Table 4 summarizes the measurements performed on Discovery (November 26, 1996). It also tabulates measurements from Atlantis (November 15, 1996) (see table 3) and adjusts them upwards to take into account the meter electronic offset adjustments. It is clear from the data that the flow rates on both WCL1 and WCL2 inlets are very similar and in agreement between the Space Shuttles Discovery and Atlantis. The flow rate results obtained from the two orbiters did not show any anomaly or unique flow situation for Discovery. Here again, the WCL1 inlet on Discovery exhibited somewhat lower readings than the rest. However, the deviation is not significant enough to cause any alarm. No further effort was expended to review this deviation.

CONCLUSIONS

Based on the noninvasive measurements and trivial differences in the flow rates observed on the two Space Shuttles, it was concluded that no further invasive troubleshooting was necessary at the present time. Also, since the observed flow rates were very close (see table 4), it was determined that damaged or pinched tubing did not contribute to the lower-than-designed flow rates observed on Discovery. Additionally, since the interval operation of the coolant loop with stagnant water is based on the calculated flow through the coldplate, the design model results (which predicted 4-hour interval operations would preclude ice formation) may have been incorrect. Based on this study, it is recommended that the thermal calculations for ice formation in the floodlight coldplate be recalculated using flow-rate numbers as low as 30 to 40 percent of the above measured values.

The NFMS greatly enhanced troubleshooting procedures and allowed for more accurate flow rate measurements with which to calculate the inflight interval operations. This may facilitate decreasing the operation interval of the coolant loop with the stagnant water, thereby significantly reducing mission costs and diverting valuable human resources to more important space operations.

Lastly, continuous and online monitoring via permanently installed sensors may further reduce the chances of experiencing a similar ice buildup in space. Design changes to improve conformity between the sensor and the pipe geometry were transmitted to the manufacturer upon the conclusion of this work.

In summary, in addition to enhancing the state of the art in flow measurement technology for extremely small diameter pipes with low flow rates, the present work successfully demonstrated the feasibility of nonintrusive ultrasonic techniques for Space Shuttle applications. Since the water coolant loop floodlight coldplate flows were never determined by in situ measurement and the present Shuttle configuration lacks an on-board flow indicator, it is recommended that these sensors be a part of future integrated vehicle health monitoring (IVHM) programs.

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13. ABSTRACT *(Maximum 200 words)*

Using a Nonintrusive Flow Measurement System (NFMS), the flow rates through the Space Shuttle water coolant coldplate were determined. The objective of this in situ flow measurement was to prove or disprove a potential block inside the affected coldplate had contributed to a reduced flow rate and the subsequent ice formation on the Space Shuttle Discovery. Flow through the coldplate was originally calculated to be 35 to 38 pounds per hour. This application of ultrasonic technology advanced the envelope of flow measurements through use of 1/4-inch-diameter tubing, which resulted in extremely low flow velocities (5 to 30 pounds per hour). In situ measurements on the orbiters Discovery and Atlantis indicated both vehicles, on the average, experienced similar flow rates through the coldplate (around 25 pounds per hour), but lower rates than the designed flow. Based on the noninvasive checks, further invasive troubleshooting was eliminated. Permanent monitoring using the NFMS was recommended.

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